

Automatic Detection of Beaked Whales from Acoustic Seagliders & Passive Autonomous Acoustic Monitoring of Marine Mammals with Seagliders

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LONG-TERM GOALS

The U.S. Navy's use of tactical mid-frequency active sonar has been linked to marine mammal strandings and fatalities (NMFS 2001). These events have generated legal challenges to the Navy's peacetime use of mid-frequency sonar, and have limited the Navy's at-sea anti-submarine warfare training time. Beaked whales may be particularly sensitive to mid-frequency sonar. A mobile, persistent surveillance system that could detect, classify and localize beaked whales will help resolve the conflict between the Navy's need for realistic training of mid-frequency sonar operators and the Navy's desire to protect marine mammal populations worldwide. Underwater gliders equipped with appropriate acoustic sensors, processing, and detection systems – "passive acoustic monitoring (PAM) gliders" – may offer a partial solution to the problem. The acoustically-equipped Seaglider™ from the Applied Physics Laboratory of the University of Washington (APL-UW) is one such platform. A Seaglider can travel about 20 km/day through the water for a period of weeks to months, dive from the surface to 1000 m and back in a few hours, and use two-way satellite (Iridium) telemetry for data and command transfer. This makes it potentially highly useful for the long-term goal of this project, mitigating impacts of Navy operations on marine mammals.

OBJECTIVES

The objective of this effort is to develop techniques for detection and classification of odontocetes echolocation clicks and especially beaked whale sounds for the PAM Seaglider. Because any methods developed must run in the operational environment of the Seaglider, they must have a low average computational cost because of the limited processing power and battery life of the Seaglider. The performance of the detection and classification system will be evaluated on several field trials.

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APPROACH

The detection/classification system for the PAM Seaglider is a two-stage system. Stage 1, click detection, is operated continuously, creating a constant load, and Stage 2, classification (verification) of detected clicks, is operated only a small fraction of the time and thus can be computationally more expensive. Stage 1 is now fully implemented in the processing environment of the Seaglider. Work on stage 2 is still ongoing.

WORK COMPLETED

Stage 1: Detection using the ERMA detector

Energy-based detection algorithms are commonly used to detect many types of sound signals, including odontocete clicks, in real time (e.g., Mellinger *et al.*, 2004). A major advantage of such algorithms is their relatively low computational cost, as they can operate in the time domain. However, for detecting a given species of odontocete, time-domain algorithms often result in a high number of false positive detections caused by clicks of other odontocete species. The energy ratio mapping algorithm (ERMA) was developed to reduce the number of false positive detections while keeping computational cost low, as is needed for long-term (weeks to months) real-time operation with the Seaglider. ERMA was tested in several bench trials (e.g., Yack *et al.*, 2010) and field trials (see below), and based on the results, modified and improved. The most recent version of ERMA includes a likelihood measurement for detected clicks. Detection function amplitudes of detected clicks, number of clicks, and mean inter-click-intervals (ICI) of clicks within detected bouts are used to rank [a] data files of one minute duration containing detections and [b] individual clicks within those files. This ranking is important for time-critical applications, such as mitigation of potential impacts to beaked whales during naval exercises. Data files associated with highest likelihood values as determined by the ERMA detector are analyzed by the classifier first. Once detections have been verified by the classifier, the glider is programmed to return to the surface as quickly as possible to report the presence of beaked whales back to a shore or ship-based control center. In addition, raw acoustic data snippets containing individual high-likelihood clicks are transmitted for manual verification. A ‘fixed point’ version of the ERMA based detector is also available and was implemented on another autonomous platform: the QUEphone developed by Haru Matsumoto, OSU. A manuscript providing an in-depth description of ERMA has been published in the Journal of the Acoustical Society of America (Klinck and Mellinger, 2011).

Stage 2: Classification

Work on the classifier is being conducted in collaboration with Marie A. Roch, San Diego State University and Scripps Institution of Oceanography.

We developed a classification system for echolocation clicks of six species of odontocetes recorded in the Southern California Bight: bottlenose dolphins (*Tursiops truncatus*), short- and long-beaked common dolphins (*Delphinus delphis* and *D. capensis*), Pacific white-sided dolphins (*Lagenorhynchus obliquidens*), Risso’s dolphins (*Grampus griseus*), and presumed Cuvier’s beaked whales (*Ziphius cavirostris*). Echolocation clicks were represented by cepstral feature vectors (14 features) that are classified by Gaussian mixture models. A randomized cross-validation experiment (*n*-fold training/testing) was designed to provide conditions similar to those found in a field-deployed system. To prevent matched conditions from inappropriately lowering the error rate, echolocation clicks associated with a single sighting were never split across the training and test data. Sightings were randomly permuted before assignment to folds in the experiment. This allows different combinations

of the training and test data to be used while keeping data from each sighting entirely in the training or test set. The system achieves a mean error rate of 22% across 100 randomized 3-fold cross validation experiments. Four of the six species had mean error rates lower than the overall mean, with the presumed Cuvier's beaked whale clicks showing the best performance ($< 2\%$ error rate). Long-beaked common and bottlenose dolphins proved the most difficult to classify, with mean error rates of 53% and 68% respectively. A manuscript providing an in-depth description of the classifier has been published in the Journal of the Acoustical Society of America (Roch *et al.*, 2011).

A C-code version of the classifier is now available for use in the Seaglider. The code has been bench tests and results showed that the ARM-9 processor is powerful enough to operate the classifier on the Seaglider. The classifier still needs to be fully implemented (handshaking with other software modules, for example, ERMA detector). Furthermore the Gaussian mixture models need to be adapted using actual Seaglider acoustic data in order to achieve good classification results.

Stage 3: SNR improvement for better detection and classification

To improve the detection rate, a novel signal-to-noise ratio (SNR) improvement algorithm has been developed. Fig. 1 shows the relationship between SNR and estimated detection rate for AUTECH data (Kusel *et al.* 2011). This figure shows that the curve is very steep when SNR is from 2-10 dB. In the low SNR range where most clicks are received, a slight increase in SNR can greatly increase the probability of detection.

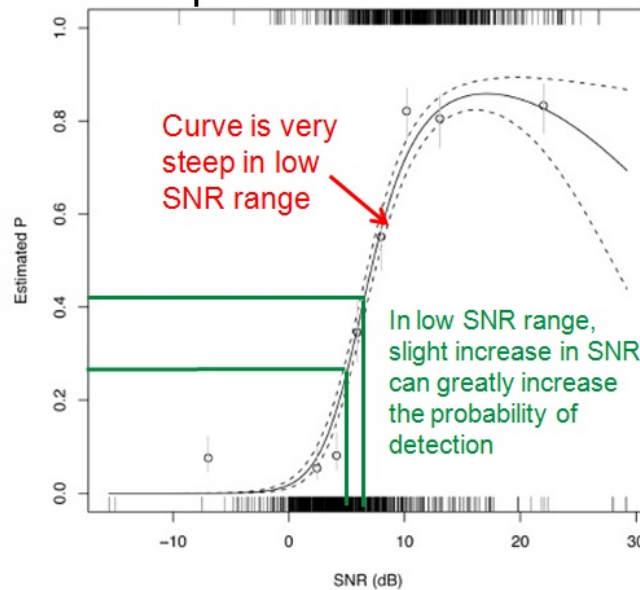


Figure 1. Probability of click detection as a function of signal-to-noise ratio (SNR). The steepness of the curve in the 2-10 dB range indicates that a slight increase in SNR can lead to a large increase in detection performance.

To improve the SNR, we first used least mean squares (LMS) filter which minimizes the mean squared of the error signal (Haykin, 2002). The LMS filter is chosen for its simple structure and low computational complexity. To further improve the SNR rate and overcome the slow convergence rate

of the LMS filter, a subspace based algorithm (Hu et al. 2002) is used. This subspace method projects the noisy received-signal vector onto signal and noise subspaces. We also developed a detector based on the mean-squared error between the data before SNR improvement and after SNR improvement.

RESULTS

1. *Field tests.* Five field tests have been conducted with the PAM Seaglider to date (Table 1).

Table 1. Overview of the 5 field trials of the PAM Seaglider conducted to date.

DEPLOYMENT	SEAGLIDER	DATES	NUMBER OF DIVES (1KM)	HOURS OF RECORDING ¹	GB OF RECORDING ²
HARO STRAIT	SG022	4SEP2009	5 (0)	2.8	3.7
KONA I	SG022	27OCT-17NOV2009	116 (102)	170.2	141.5
KONA II	SG022	16MAR-26MAR2010	61 (42)	101.8	84.6
	SG023		94 (36)	107.1	89.0
AUTEC	SG178	7JUN-11JUN2010	35 (12)	58.5	48.6
	SG179		27 (12)	71.7	59.6
SCORE	SG178	4JAN-7JAN2011	30 (19)	56.2	46.7
	SG179		30 (19)	53.5	44.5
TOTAL		56 DAYS	398 (223)	621.8	518.2

¹Duty-cycle governed by detect_below parameter
²Sample rate = 194162 samples per second, 16-bit A/D conversion, FLAC encoding (ratio ≈ 0.6)

While the two tests off Kona, HI were primarily driven by engineering tests, the AUTEC trial was specifically designed to evaluate the detection performance and detection radius of the Seaglider. We deployed two Seagliders in the northwest corner of the AUTEC range and operated them continuously for 5 days. One glider was programmed to hold its position on top of the Whiskey 1 array ('stationary glider') while the second glider ('transecting glider') conducted East-West transects across the 'Tongue of the Ocean' basin. The experiment was highly successful: a total of 23 encounters with beaked whales were detected by the two Seagliders. The Whiskey 1 array features a closer hydrophone spacing which allowed us to locate vocalizing whales. These data were used to estimate the distance between the glider and the whales and to evaluate the detections performance and radius of our system.

2. *Data analysis.* The Kona I data set (see Table 1) has been analyzed and a manuscript describing the results is in preparation. During the Kona I trial beaked whales were successfully detected in real time and their presence was reported back to shore. The data sets recorded during the Kona I and II missions are currently also being specifically analyzed for false killer whales by Erin Oleson, NOAA/NMFS/PIFSC.

Results from the AUTECH 2010 glider data analysis revealed that (a) the detection likelihood for beaked whales significantly increases with depth – in fact, almost all detection occurred at depth 300 m or deeper; and (b) the maximum detection radius of the Seaglider is likely in the range of 4 km, a distance which agrees with results from theoretical models (Zimmer *et al.* 2008). The glider's detection radius was estimated by comparing distances at the time of detection between the glider and the closest AUTECH hydrophone which registered beaked whale activity. NAVSEA/NUWC is working on extracting actual beaked whale locations from the recorded AUTECH M3R data set, locations that will allow us to calculate actual distances to vocalizing animal/groups.

3. *Visualization.* A tool was developed (Fig. 2) to visualize glider surveys to make it easier to identify spatiotemporal patterns. This tool animates gliders along their travel paths, and also shows the bathymetry of the area and any other instruments present such as hydrophones, QUEphones, etc. Hydrophones that register a glider detection are shown in a different color, allowing easy visualization of the match between glider detections and fixed-hydrophone detections of target species.

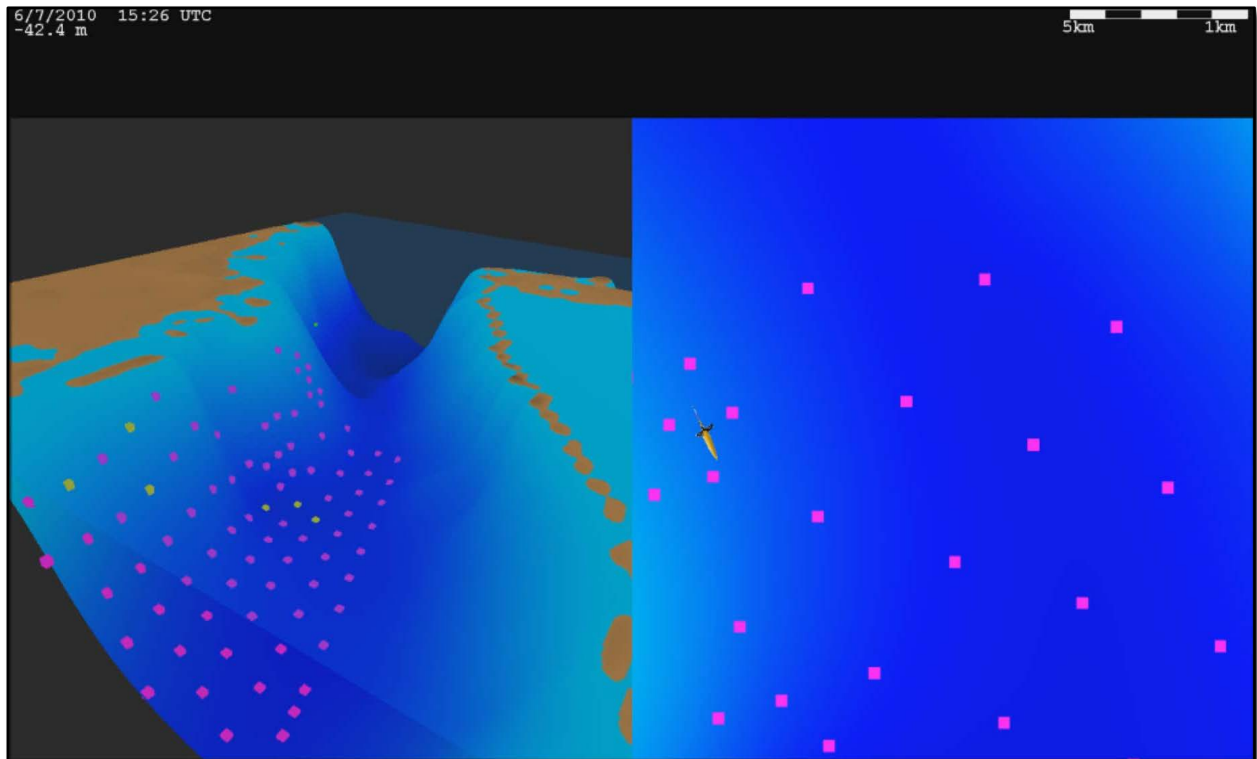


Figure 2: Screenshot of a single frame of the glider visualization animation tool showing the AUTECH hydrophone array and glider positions in both perspective (left) and plan (right) views. Hydrophones colored yellow are registering beaked whale detections.

4. *SNR improvement for better detection and classification.* Table 2 shows the SNR improvement for beaked whale clicks at AUTECH. In both datasets, over 60% of the clicks have SNR improvement, with an average SNR increase of 0.4 dB. The detection probability is not significantly improved after the noise reduction algorithm. One possible reason is the average SNR of the data tested is around 12 dB. Based on Fig. 1, there is not much improvement in detection probability for SNR larger than 10 dB. Also through simulations, the proposed detector is shown to be capable of detecting most of the desired clicks, but is not able to differentiate other co-existing species such as Risso’s dolphins and pilot whales – that is, it efficiently detects *all* clicks. By combining the proposed detector with the Energy Ratio Mapping Algorithm (ERMA; Klinck et al. 2011), which measures energy differences between different species, higher detection accuracy for beaked whale clicks can be achieved. This is shown by the Detection Error Tradeoff (DET) curve in Fig. 3.

Table 2. Improvement in SNR with the subspace filtering algorithm. Improvement is not dramatic, but as Fig. 1 shows, not much change is needed to significantly improve detection. “SNR improvement rate” indicates the percentage of clicks whose SNR improves with filtering; the remainder have either the same or a lower SNR after filtering.

species	dataset	duration	no. of clicks	avg. SNR	avg. SNR improvement	SNR improvement rate
Blainville’s beaked whale	Set4-A6-092705-H76-0155-0214-1030-1049loc_0300-0600min	180 s	1770	12.7 dB	0.5 dB	80.27%
Blainville’s beaked whale	Set4-A7-092705-H84-0155-0214-1030-1049loc_0230-0430min	120 s	1012	12.4 dB	0.26 dB	63.76%

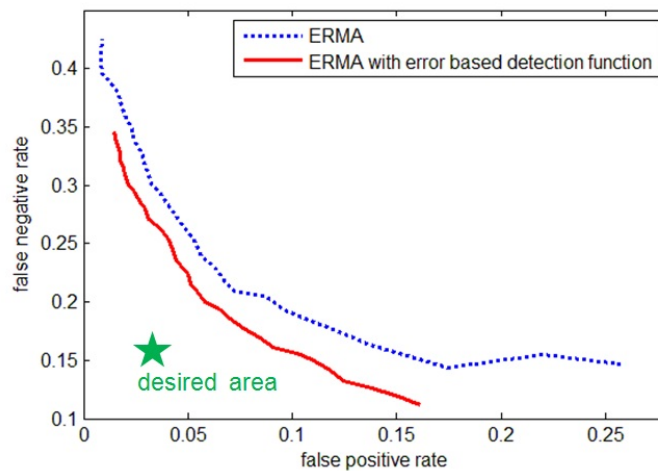


Figure 3. The Detection Error Tradeoff curves for detection with and without use of information from the subspace filtering algorithm, showing that filtering significantly improves performance. Curves closest to the lower left corner indicate best performance.

IMPACT/APPLICATIONS

It is hoped that a “marine mammal Seaglider” will be useful for the conservation of cetaceans by revealing their presence before, during, and after Navy operations, thus allowing for the use of mitigation measures to prevent harm to them. It is also hoped that Seagliders equipped with the detection technology developed here will be more broadly useful, perhaps for monitoring marine mammal population changes, studies of the seasonal distribution of marine species, marine mammal behavioral observation, and other applications that we have not yet anticipated.

RELATED PROJECTS

We are closely collaborating with the projects “Acoustic Seaglider for Beaked Whale Detection” (award N00014-08-1-0309) and “Passive Autonomous Acoustic Monitoring of Marine Mammals: System Development using Seaglider” (award N00014-10-1-0515), with PIs Neil Bogue and Jim Luby of the Applied Physics Laboratory, University of Washington. The Bogue/Luby group is (1) developing and testing a new processor architecture for the Seaglider, (2) developing and testing an associated new multi-channel acoustic recording system for the Seaglider, (3) leading the fieldwork to test deployments of the “marine mammal Seaglider”. We are primarily developing algorithms for detecting beaked whales and other odontocetes from the Seaglider and implementing these algorithms in the Seaglider’s processing environment, while UW is developing hardware, building the acoustic processing environment, and operating the Seaglider.

The ONR-funded project “Acoustic Float for Marine Mammal Monitoring” (award N00014-08-1-1198, P.I. Dr. Haru Matsumoto, OSU) is also using the ERMA detector described above. It is implemented differently in the two projects, mainly because of different processor architectures used in the PAM boards of each instrument.

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HONORS/AWARDS/PRIZES

Dr. Klinck was promoted from Postdoctoral Associate to Assistant Professor at Oregon State University in 2011.